# Exploration of the Solar System

## Science and Mission Strategy

December, 1999

# INTRODUCTION

This document summarizes the scientific objectives and programmatic recommendations for the Exploration of the Solar System. It was intended as input to the NASA Office of Space Science planning workshop, held November 2-4, 1999, in Galveston, Texas. A companion technology roadmap will be published early in the year 2000.

# Executive Summary

**The three Quests for the Exploration of the Solar System:**

***Explain the Formation and Evolution of the Solar System and the Earth Within it;***
***Seek the Origin of Life and its Existence Beyond Earth;***
***Chart our Destiny in the Solar System***

**provide a framework for a compelling program of exploration and scientific research. The Quests are founded on a robust Research and Analysis program and are the basis for an engaging series of Education and Outreach activities.**

**The missions for the Exploration of the Solar System are conducted within Programs. Three of these Programs exist today, and this Roadmap establishes scientific direction and mission recommendations for their future activities. The Roadmap recommends the establishment of an important new Program called "To Build a Planet", within which the highest priority new mission is Comet Nucleus Sample Return. The Roadmap also recommends immediate new investments in the facilities and capabilities for handling and analyzing the Mars samples that will arrive on Earth in 2008.**

**The capabilities and technologies required for these missions and for future exploration are summarized here, and will be described in greater detail in the companion Technology Roadmap that is in preparation.**

**The Exploration of the Solar System is a search for Origins…of the planets, of environments for life, and of life itself. It provides context and ground truth for the astronomical search for Origins and for the study of other solar systems. And it is a critical component of an integrated space science strategy that addresses the questions**

***Where did we come from...?***
***Where are we going...?***
***Are we alone?***

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# The Solar System Exploration Program

... seeks answers to fundamental questions about the Solar System and life:

**How do planets form?**

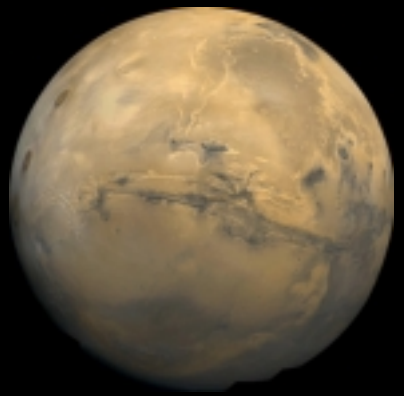
**Why are planets different from one another?**

**Where did the makings of life come from?**

**Did life arise elsewhere in the Solar System?**

**What is the future habitability of Earth and other planets?**

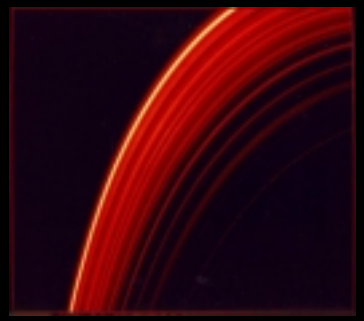
# The Search for Origins in Our Solar System

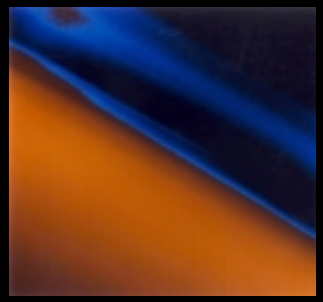




**To answer these questions, the Solar System Exploration Program seeks to understand the Origins and evolution of**

- **the planets and other bodies of our solar system, including Earth;**
- **environments habitable by any form of life; and**
- **life itself,**

**and how solar system processes affect the future of Earth and humanity.**





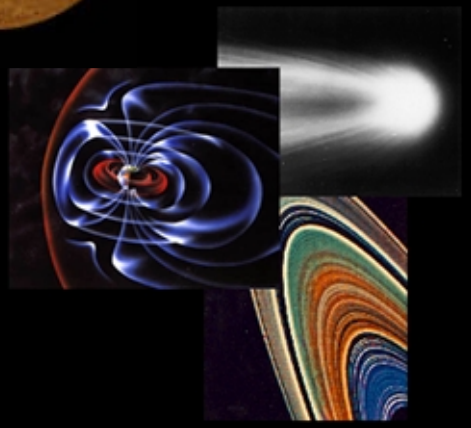
# "Ground Truth" for the Astronomical Search for Origins

The *planets* and other bodies of our solar system comprise the only planetary system *known* to contain life, and provide "ground truth" for the study of habitable environments and planetary systems around other stars.

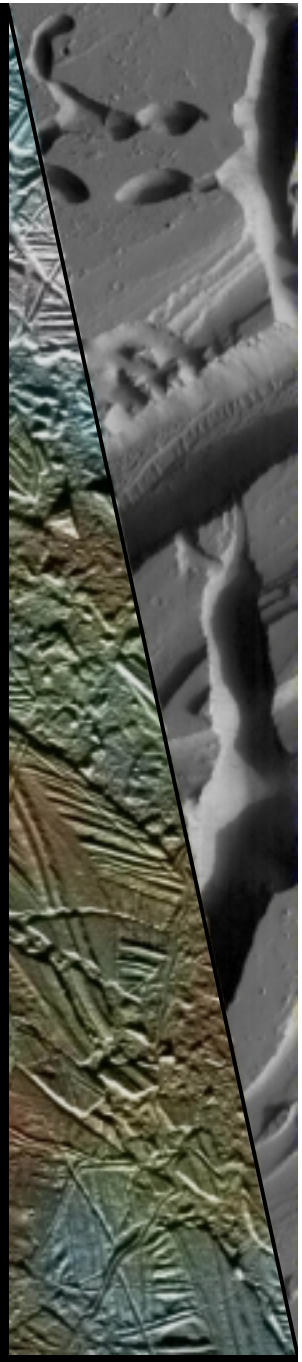
The Earth in context

Diversity of planets

Records of formation



Dynamical models



Water in the solar system

# THE QUESTS

# The Solar System Exploration Program Conducts Three Quests for Knowledge:

**Quest 1:**
**To Explain the Formation and Evolution of the Solar system and the Earth Within It**

**Quest 2:**
**To Seek the Origin of Life and Its Existence Beyond Earth**

**Quest 3:**
**To Chart Our Destiny in the Solar System**

# Quest 1: Explain the Formation and Evolution of the Solar System and the Earth Within It

## Goals:

- Understand the origin of the solar nebula and the forces that formed Earth and the other planets

- Determine the processes that led to the diversity of solar system bodies and the uniqueness of planet Earth

- Use the exotic worlds of our solar system as natural science laboratories

*The state of the modern Solar System results from the complex interplay of diverse processes--including those governing the formation, evolution, and interactions of gas giant and terrestrial planets, their satellites, and smaller bodies of ice and rock.*
*These same processes determine the existence of habitable environments.*

# Quest 1: Explain the Formation and Evolution of the Solar System and the Earth Within It

The state of the present solar system results from the complex interplay of diverse processes - including those governing the formation, evolution, and interactions of gas giant and terrestrial planets, their satellites, and smaller bodies of ice and rock. These same processes determine the existence of habitable environments.

How do planets form and why do they differ from one another? To answer these fundamental questions we must study both the records of the ancient solar system and today's active processes. We know that planetary systems begin as interstellar molecular clouds; the collapse of these clouds leads to the formation of protoplanetary disks; within these disks planetesimals form, and some of these planetesimals accrete to form planets. Others are left behind and may be seen billions of years later as asteroids and comets. As this process proceeds, the physical scale of the critical phenomena narrows from one as vast as the space between the stars down to the size of an individual planet and its immediate environment.

Planet formation is the central step. Once that has occurred, subsequent planetary evolution leads to widely varying outcomes. Partly these differences are due to the planets' location in the Solar System, and partly they are due to evolution specific to each planet itself. Geological, climatological, and biological evolution are linked and help shape one another. After billions of years of competition and synergy between these processes, the worlds of our solar system have evolved to their current broad, diverse outcomes.

Pursuing this Quest means understanding these processes, and this requires that we study those key destinations at which the processes can be observed. For example, understanding planetesimal formation requires that we visit asteroids, comets, and the Kuiper Belt, the vestigial planetesimals remaining in our solar system. Close-up study of Saturn's rings allows us to witness directly disk system dynamics and the physics of collisions as well as the beginning stages of planet formation. Exploring the disparate evolution of planetary geologies and atmospheres helps us understand divergent planetary outcomes. These destinations in turn imply certain missions of exploration, and these are the missions we recommend for the future exploration of the Solar System.

The recent discoveries of extrasolar disks and planets, and the scientific benefit of providing ground truth for these studies through study of our own solar system, inform our mission recommendations and helps provide a foundation for an integrated space science strategy.

# Quest 1 - Explain the Formation and Evolution of the Solar System

## Process

Interstellar Molecular Clouds

Formation of Protoplanetary Disks

Planetesimal Formation

Protoplanetary Evolution

Planet Formation

Planetary Evolution

Time

Geological Evolution

Climate Evolution

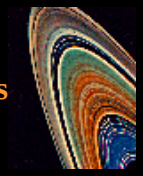
Biological Evolution

Diverse Planetary Outcomes

*- How do planets form and why do they differ from one another ? -*

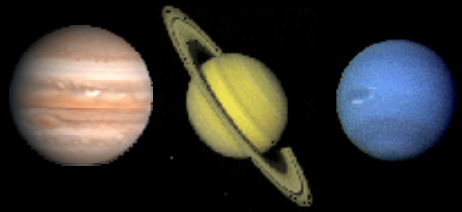
## Key Destinations

Ring systems



Asteroids, Comets and Kuiper Objects

Giant Planets



Mercury

Moon

Venus

Mars

Earth

# Research and Analysis

The Solar System Research and Analysis programs support the scientific research, theoretical development, modeling, data analysis and distribution, and archiving that is the foundation of Solar System Exploration. These programs provide knowledge that contributes to our Quests at every phase, including the definition of questions to be addressed by the missions; development of models and measurement strategies; development of instrument concepts and technologies; initial data analysis in conjunction with mission operations; longer term data analysis, dissemination, and archiving. Research and Analysis programs provide crucial support for researchers and students throughout the solar system science community and thus help to ensure that our nation continues to lead the world in science, technology, and exploration.

The elements of Solar System Research and Analysis are:

Core discipline science programs: Planetary Geology and Geophysics; Cosmochemistry; Planetary Astronomy; Planetary Atmospheres; Astrobiology (cross-theme)

Data analysis programs, currently including Mars, Lunar, and Jupiter data analysis

Space science data services: The Planetary Data System

Planetary Instrument Definition and Development

Ground based and sub-orbital observations

Participating scientist and guest investigator programs

# Research and Analysis Role in Exploration of the Solar System


## R&A contributions

Theoretical modeling, identifies new knowledge needed, defines program gaps

Modeling and correlative studies of prior mission data to help define detailed mission requirements and constraints

Short term, quick-look analysis for early results from mission data

Detailed studies support next cycle and point to missions needed to answer important new questions. Instrument development programs enable new capabilities. Space Science Data System archives data and provides documented data to investigators.

# Strategic Importance of the R&A Programs

**Examples of contributions to Quest 1: Explain the formation and evolution of the solar system and the Earth within it**

**Planetary Geology and Geophysics**

- Document the evolution of solar system bodies
- Constrain the mechanics and processes of planet formation
- Determine the processes shaping planets through time

**Cosmochemistry**

- Constrain the timing and mechanism of accretion and differentiation, melting and recrystallization of solar system bodies
- Provide theoretical constraints on terrestrial planet atmosphere evolution

**Planetary Astronomy**

- Inventory and determine the composition of the building blocks of the solar system
- Explore planetary environments and the processes of solar system evolution

**Planetary Atmospheres**

- Understand the processes that account for diversity among planetary atmospheres
- Understand the relationships between giant planets and brown dwarfs
- Determine atmospheric sputtering processes of planets with thin atmospheres

**Astrobiology**

- Determine the organic contribution to planets from primitive bodies

# Astrobiology and Solar System Exploration:

## How Quest 1 contributes to the study of life in the Universe

Our solar system is a habitat for life. It may be unique or one of many, and life may have developed in just one or several environments. In any case, an understanding of the origin of our solar system, and the chemical and physical processes through which it has evolved, is central to a complete understanding of the formation and development of life. The centuries-old study of our planetary neighborhood and the emerging science of Astrobiology -- the study of life in the Universe -- are thus inextricably linked. We know that life and its environment are intimately coupled, and that each adapts to the other in a complex manner. The study of our solar system's ancient records and active processes complements lab research into life's origins, forming a compelling framework to address one of life's greatest mysteries: where did we come from?

# Astrobiology and Solar System Exploration

**Quest 1:** ***Explain the Formation and Evolution of the Solar System and the Earth Within It***

...helps to answer the first of Astrobiology's three Fundamental Questions:

***How does life begin and develop?***

***From the Roadmaps:***

| **Exploration of the Solar System:** | | **Astrobiology:** |
|---|---|---|
| **Goals for Quest 1** | …address... | **Goals** |
| Origin of the solar system and Earth | | 1.) How life arose on Earth<br>*and*<br>4.) Co-evolution of biosphere and Earth |
| Formation and evolutionary processes, planetary diversity, and uniqueness of Earth | | 4.) Co-evolution of biosphere and Earth<br>*and*<br>6.) Nature of habitable planets |

# Quest 2: Seek the Origin of Life and Its Existence Beyond Earth

## Goals:

- Understand the sources and reservoirs of water and organics - the building blocks of life

- Determine the planetary conditions required for the emergence of life

- Search for evidence of past and present life elsewhere in our solar system

*Study of how **life** formed on Earth guides our search for evidence of life elsewhere in the solar system.*

# Quest 2: Seek the Origin of Life and its Existence Beyond Earth

Study of how life formed on Earth guides our search for evidence of life and its processes elsewhere in the solar system

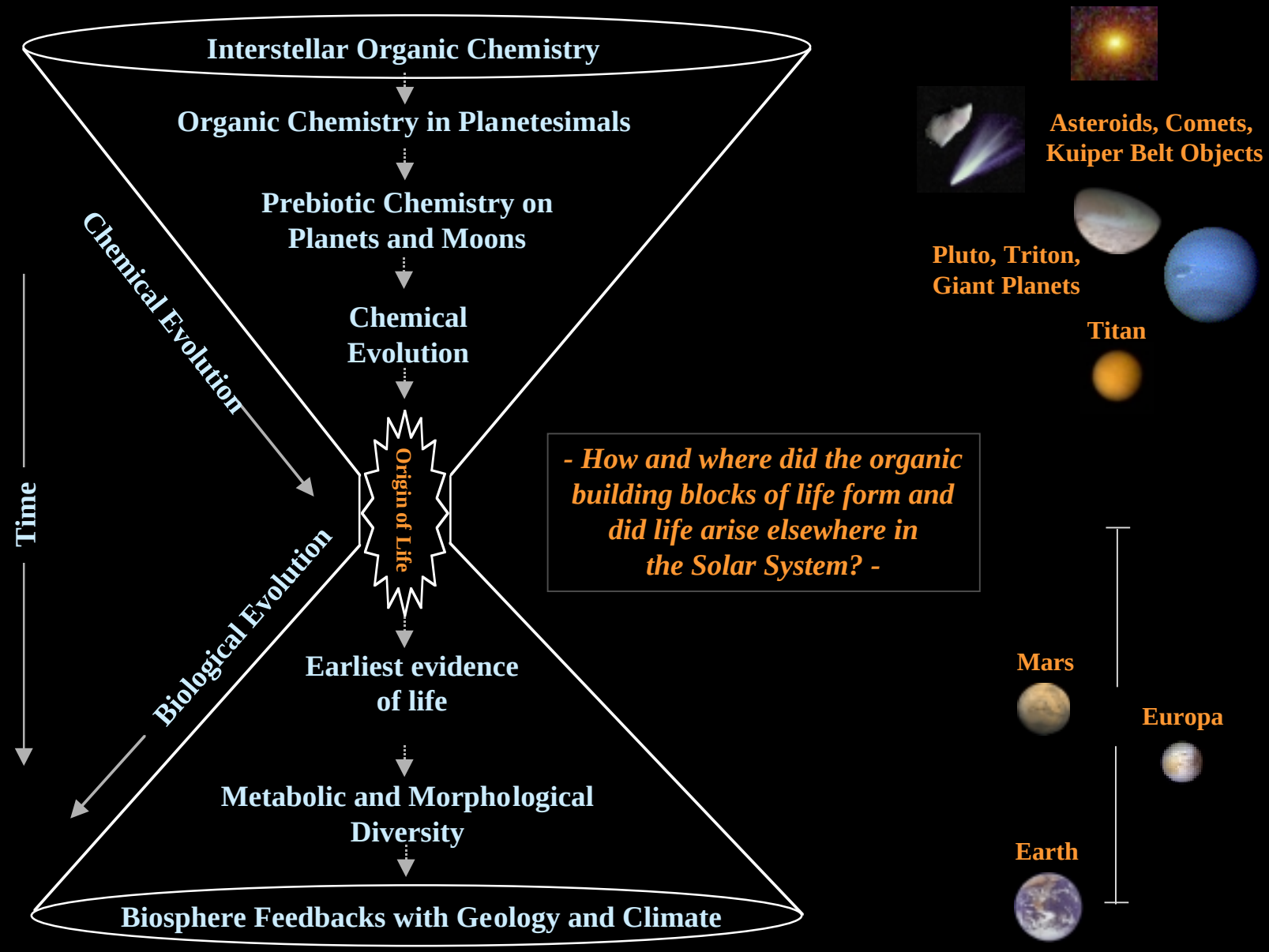
How and where did the organic building blocks of life form? Did life arise elsewhere in the Solar System? No single mission or even set of missions can provide full answers to these questions. Rather, we must study the complex series of processes that begins with interstellar organic chemistry and ends, in some cases, with biospheres that can influence the climates of entire worlds.

The origin of life in the solar system has roots in the organic chemistry of the interstellar medium; this organic chemistry contributes to the organic chemistry of comets and asteroids (and hence meteorites); and these objects in turn make a contribution to the *in situ* organic chemistry occurring on planets and moons in the Solar System. On some worlds further chemical evolution takes place, and on some of these the chemical systems become self-replicating and life forms. As these processes proceed, the physical scale of interest gradually narrows from the scale of interstellar organic chemistry down to local events such as the first development of self-replication in a particular environment.

The origin of life is the critical step. Once that has occurred, biological evolution proceeds through an increasing variety of organisms. These organisms grow more diverse, both metabolically and morphologically. Finally, on those worlds like the Earth where biology flourishes, a planetary biosphere may become a powerful influence on the climate and even the geology of an entire world.

Pursuing this Quest means seeking to understand these processes. Key destinations include Titan, the one place in the solar system where prebiotic chemistry appears to occur in an atmosphere that may resemble, in some ways, that of Earth at the time of the origin of life. We must therefore go to Titan to study prebiotic chemical evolution on a planetary scale. Similarly, Mars and Europa may provide insight into simpler planetary biospheres that never developed into the globally transforming biosphere of Earth. Just as important, if life never developed on these worlds, we may learn about the various factors that can prevent life from forming.

# Quest 2 - Seek the Origin of Life and its Existence Beyond Earth



# Strategic Importance of the R&A Programs

**Examples of contributions to Quest 2: Seek the origin of life and its existence beyond Earth**

**Planetary Geology and Geophysics**

- Search for past/present habitats on Mars and beyond
- Constrain the inventory and history of volatiles in the Solar System

**Cosmochemistry**

- Find environments and conditions where life might have developed or exists
- Constrain the formation and evolution of the building blocks of life
- Model the climate history and habitability of planetary bodies

**Planetary Astronomy**

- Inventory organic-rich environments in the solar system
- Inventory volatiles in the solar system

**Planetary Atmospheres**

- Understand how past atmospheres would have been hospitable to life
- Model the circulation of atmospheres to constrain their habitability

**Astrobiology**

- Investigate prebiotic organic chemistry; model potential for chemical evolution on Titan
- Seek the limits and potential habitats for life
- Address the question of where life can emerge and how it might be transported between planets

# Astrobiology and Solar System Exploration:

## How Quest 2 contributes to the study of life in the Universe

Recent discoveries have reinforced the concept that life is tremendously robust and adaptable. Anywhere on Earth that we find its fundamental requirements - organic material, liquid water, and a source of useable energy - we also find life. It exists in extreme and inhospitable environments on Earth, environments that resemble those found elsewhere in the solar system. Our study of the origin, evolution, and diversity of environments in the solar system can tell us much about the conditions and processes that allow life to thrive or that impede its progress. It will help us to understand where life may have developed in our solar system, why it presently exists in profusion only on Earth, and how we might identify other solar systems in which life may have taken hold.

# Astrobiology and Solar System Exploration

**Quest 2:** ***Seek the Origin of Life and its Existence Beyond Earth***

…helps to answer the first two of Astrobiology's three Fundamental Questions:

**How does life begin and develop?**

**Does life exist elsewhere?**

***From the Roadmaps:***

| **Exploration of the Solar System:** | | **Astrobiology:** |
|---|---|---|
| **Goals for Quest 2** | …address... | **Goals** |
| Water and organics in the solar system | | 1.) How life arose on Earth<br>*and*<br>5.) Limits for life |
| Planetary conditions for life | | 6.) Nature of habitable planets<br>*and*<br>7.) Signatures of life |
| Evidence of past or present life | | 7.) Signatures of life<br>*and*<br>8.) Life on Mars and Europa |